Development of a Field Method for Evaluating Nonlinear Properties and Liquefaction Resistance of Near-Surface Soils

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Investigations Undertaken

The goals of this project are to develop field methods that can be used to: 1. evaluate the nonlinear response of soils and 2. evaluate the liquefaction resistance of soils. At this time, the field methods under development are aimed at testing near-surface soils; that is, soils within 0.5 to 3 m of the ground surface.

The project has begun with developing a generalized test method to measure nonlinear soil properties. This method involves applying static and dynamic loads at the surface of the soil deposit being tested, and measuring the dynamic response of the soil mass beneath the loaded area using embedded instrumentation. A vibroseis truck is used to apply static and dynamic loads to a large circular footing at the ground surface. A vibroseis truck is an electro-hydraulic shaker used in oil exploration as a seismic source for reflection studies. The instrumentation includes a load cell to measure the loading applied to the footing and embedded velocity transducers (geophones) under and around the loaded area to measure the response of the soil mass. (In future testing, pore water pressures will be also monitored in saturated soils using piezometers.) The result is a load-controlled dynamic field test that induces soil nonlinearity within a predetermined instrumented zone.

The initial testing presented herein focuses on vertically loading the soil, evaluating the magnitude of induced strains, and assessing the variation of constrained compression wave (P-wave) velocity with effective vertical stress and vertical strain. The research team chose to study P-wave velocity rather than shear wave (S-wave) velocity in this initial work because it is more straightforward to measure P-wave velocity with the vertically oriented vibroseis truck owned by the University of Texas. Evaluating in situ material damping was beyond the scope of this initial test series, but it is certainly a priority in the next set of tests.

Test Setup

The initial test series was performed at a local granular soil quarry in Austin, Texas. A circular, reinforced concrete footing was constructed at the site to transfer load from the hydraulic ram of the Vibroseis to the ground surface. The footing was 4 ft (122 cm) in diameter, 1 ft (31 cm) thick, and was embedded approximately 6 in. (15 cm) into the ground. The vibroseis truck was placed over the concrete footing and the loading ram from the truck was lowered onto a steel frame which was used to distribute the load across the footing. A load cell was placed between the ram and steel frame to measure the load levels. The vibroseis truck and concrete footing in its loading position are shown in Figure 1.

Before the concrete footing was constructed, 11 velocity transducers (geophones) were embedded at various locations and depths below the ground surface. These geophones were encased in acrylic cases to protect the instrumentation and to allow them to be oriented accurately in the ground. Three vertically oriented geophones were placed in a vertical array beneath the center of the footing (V1, V2, and V3). Eight geophones were placed within approximately one radius from the edge of the circular footing. These eight geophones were placed in four cases, each case containing a horizontal geophone (oriented radially) and a vertical geophone. The four, two-component cases were installed at two radial distances and at two depths, to form a 61 cm by 61 cm square element outside the radius of the footing. The vertical geophone array beneath the center of the footing was used to study constrained compression wave propagation. The array of two-dimensional geophones was used to evaluate shear strains within the square element.

Figure 1. Vibroseis truck in loading position.

The soil at the test site is poorly graded sand (SP) with 3% finer than the #200 sieve. The soil is tan in color and has occasional rounded, gravel-sized particles that amount to less than 1% of the soil mass. The upper 15 cm of the soil is a cemented crust. The groundwater table is at a depth of about 1.5 m. Between the crust and the groundwater table, the soil shows a zone of capillarity, where the water content varies from about 3% to 7%. Downhole and crosshole seismic testing indicate an initial compression wave velocity of about 267 m/s and an initial shear wave velocity of 183 m/s in the sand between15 cm and 1.22 m.

Results

Variation of V_P with Vertical Effective Stress

The effective stresses in the direction of wave propagation and particle motion have a significant influence on measured body wave velocities in soil. For a vertically propagating compression wave, the directions of wave propagation and particle motion are vertical. Therefore, the vertical effective stress is the only relevant stress component that affects P-wave velocity in these tests. Measure wave velocities at relatively small strains ($\varepsilon_a < 0.005$ %) were used to investigate this relationship in situ.

Compression wave velocities measured with the shallow receivers (V1-V2) are presented in Figure 2 for all frequencies of loading. A power law relationship between P-wave velocity and effective stress is generally presented as:

$$V_P = C\,(\sigma'_a)^m \qquad (1)$$

where C is a material constant, σ'_a is the effective stress in the direction of wave propagation, and m is the slope of the log V_P -log σ'_a relationship. This power law relationship is shown in Figure 2. The relationship is fit through the downhole seismic data, using a value of m = 0.25. This value of the parameter m in Figure 2 fits the average data well, indicating good agreement with Equation (1).

Variation of V_P with Vertical Strain

The effect of vertical strain on P-wave velocity is shown in Figure 3 for receivers V1-V2. The general trend is a decrease in P-wave velocity with increasing strain level. To combine data from different static load levels, a stress correction was incorporated. The stress correction procedure involves using the power law relationship presented in Equation (1). The P-wave velocity was stress-corrected by the factor $(\sigma_a')^{m}$, using the calculated vertical effective stress and m = 0.25. This stress correction allows data to be plotted on one graph, regardless of the in situ static effective stress. For comparison, the measured downhole P-wave velocity is shown at a strain level of 0.0001%. The strain level of 0.0001% was selected to represent the very small strains generated in field downhole seismic tests.

The P-wave velocities measured between V1-V2 at different loads levels clearly exhibit nonlinear behavior as seen in Figure 3. The general trend in Figure 3 is a reduction in stress-corrected V_P with increasing vertical strain. To evaluate this nonlinear trend, typical hyperbolic functions predicted from nonlinear laboratory data were generated and fit through the downhole data as a starting point. These functions bound the vibroseis data as shown in Figure 3. Hence, the in situ measurements show the same nonlinear trend as predicted from laboratory tests.

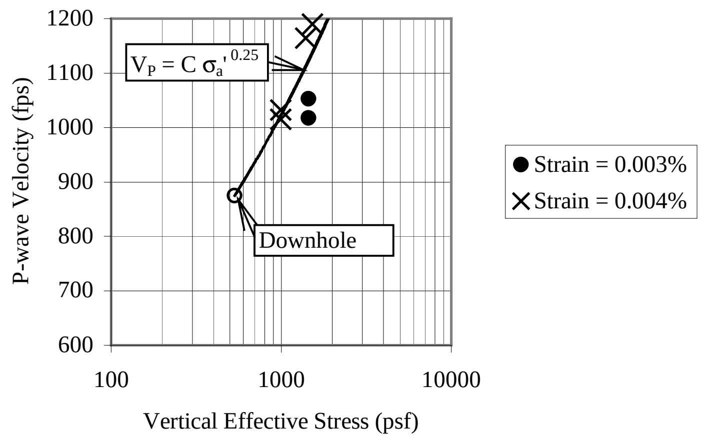

Figure 2. V_P vs. effective stress for receivers V1-V2.

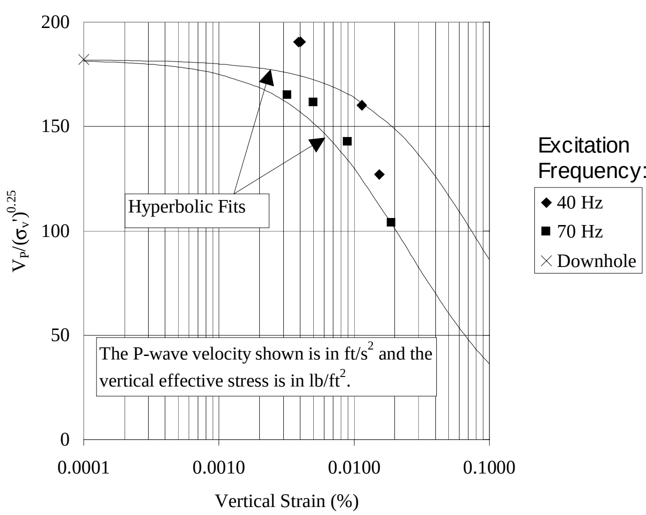

Figure 3. Stress-corrected V_P vs. vertical strain for receivers V1-V2.

Conclusions

The testing procedure and methods of data analysis are still in development, but this initial test series has lead to several important conclusions regarding the design of an in situ testing procedure to measure nonlinear soil properties. With further tests, it should be possible to measure more material properties, such as shear wave velocity and material damping in shear and compression, and draw conclusions about dynamic soil behavior and in situ states of stress for coarse-grained soils. Upon refinement of the testing method, generation of pore water pressures for the purpose of in situ liquefaction evaluation will be possible. Data from test involving the generation of pore water pressure will be extremely useful in understanding liquefaction and refining liquefaction evaluation techniques.

Non-Technical Summary

Evaluation of the earthquake response of soil sites requires knowledge of the stiffness and damping characteristics of the soil. At this time, there is total dependency on laboratory testing with small specimens to evaluate these characteristics. One goal of this project is to develop a field method to evaluate the stiffness and damping characteristics. Initial field testing has focused on applying a series of dynamic vertical loads to a 1.2-m diameter footing on the ground surface and measuring the soil behavior beneath the footing with embedded instrumentation. This work shows the general approach is sound and additional testing is underway.

Reports Published

Phillips, R.D. and Rathje, E.M. (2000). "Initial Design and Implementation of an In Situ Test for Measurement of Nonlinear Soil Properties," Geotechnical Engineering Report, GT00-1, Civil Engineering Department, University of Texas at Austin, Austin, Texas.

Paper to be Published

Rathje, E.M., Phillips, R.D., Chang, W.-J. and Stokoe, K.H., II (2001). "Evaluation Nonlinear Soil Response in Situ," Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, CA, March 26-31 (to be published).

Availability of Processed Data

All processed data is available in Phillips, 2001 in graphical and tabular forms. The contact person is Professor Ellen Rathje, she can be reached at 512-232-3683 and by e-mail at e.rathje@mail.utexas.edu.